Novel Ice Detection Methodology and System for Safer and Greener Aviation

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Outline

- Motivation
- Feasibility of an ice detection system based on the aircraft performance (operational flight data)
- Overview of the proposed detection methodology
- Results in simulation
- Summary and outlook

Motivation

- Hazardous effects of ice accumulations caused various accidents in the past

- Goal: **early detection of ice accumulations**

→ Providing necessary information to maintain safe flight conditions

→ Enabling more selective activation of anti-ice systems with reduced energy consumption

- Requirements:

→ Reasonable impact on operating costs

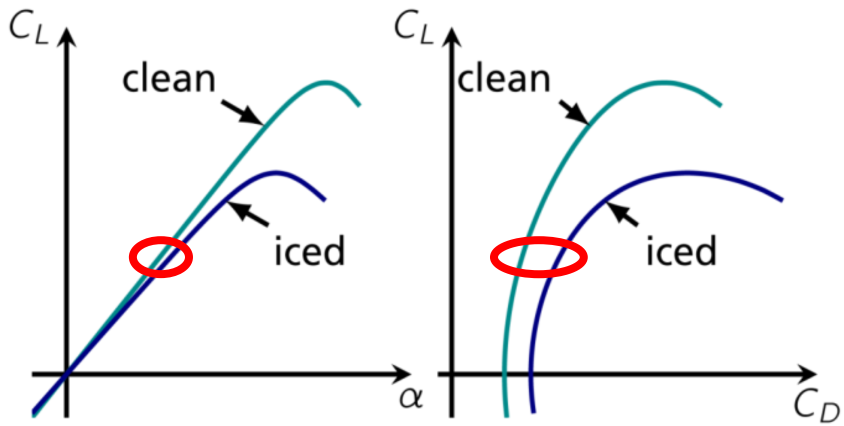
→ If possible, retrofit capability

Reduced impact of icing on aviation safety and better use of current anti-ice systems

http://grcimagenet.grc.nasa.gov/share/scr_stillimages_detail.cfm?year=1992&cnumber=2275&c_numbertextdisplay=C-1992-2275&dis_opts=shoicons&maxcnumber=2882&maxcyear=1992 (downloaded 04.10.2012)

National Aeronautics and Space Administration
Lewis Research Center

Feasibility of an Ice Detection System Based on the Aircraft Performance: Basic Principle



Change of lift (resp. pitching moment) coefficient derivatives (C_{L_α} , C_{m_α})

\+ Almost fully conserved within linear dynamic models
➔ direct use of the tools from the linear control theory possible

\- Also significantly impacted by other phenomena
➔ not specific enough

\- Excitation needed for proper detection (steady flight is an issue)

Change of drag polar (glide ratio)

Remark: Information lost during linearization

\+ Seems to characterize very well the effects of ice accretion
(variation under real conditions due to all kinds of other effects validated with a data-mining approach on FDR data)

\+ Detection during steady flight conditions

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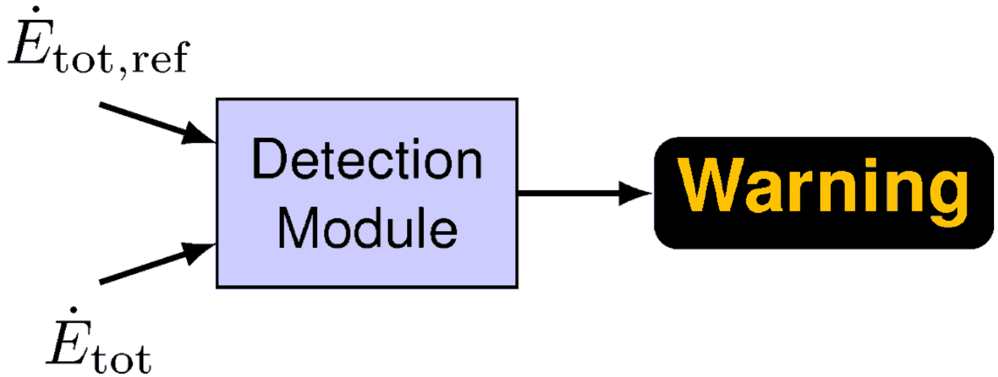
Performance-Based Detection of Icing

Equivalent additional drag:

$$\Delta C_{\tilde{D}} \approx \frac{\dot{E}_{\text{tot,ref}} - \dot{E}_{\text{tot}}}{V_{\text{TAS}} \cdot \overline{q} \cdot S_{\text{Wing}}}$$

Performance Reference



Performance State

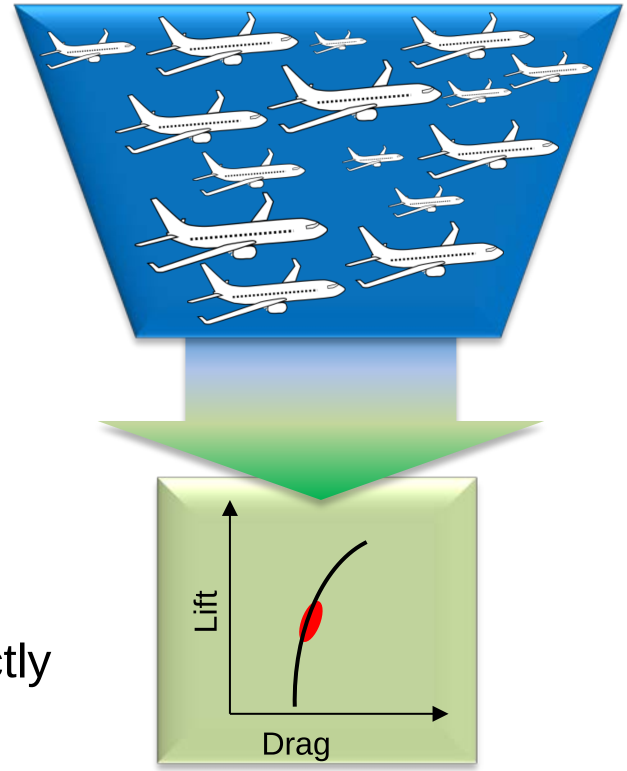
Is the filtered equivalent additional drag above the detection threshold?

$$\dot{E}_{\text{tot}} = V_{\text{TAS}} \cdot \dot{V}_{\text{TAS}} \cdot m_{\text{AC}} + \frac{1}{2} \cdot V_{\text{TAS}}^2 \cdot \dot{m}_{\text{AC}} + g \cdot \dot{H} \cdot m_{\text{AC}} + g \cdot H \cdot \dot{m}_{\text{AC}}$$

Feasibility of an Ice Detection System Based on the Aircraft Performance: (Big) Data Analysis

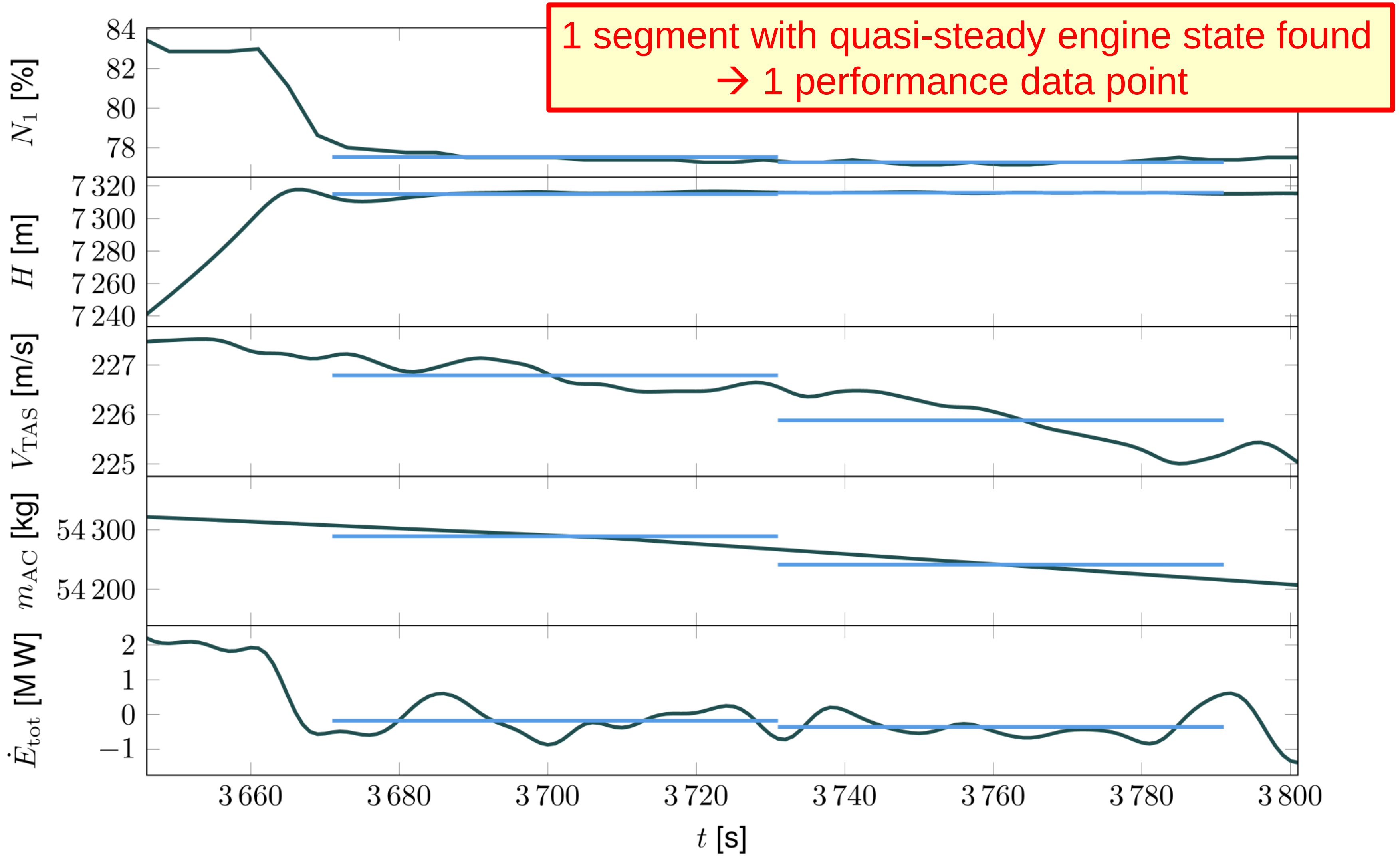
- Questions:
  How large is the performance variation that can be observed within a complete fleet during regular airline operations? (Incl. sensor errors & calibration)
  Can an ice detection system based on performance be reliable?

- Challenges related to this particular data set
  - Data discretization and quantization
  - Missing engine thrust model
  - Data were partly anonymized
    - Flight ←→ Aircraft relationship unknown
    - No possibility to track a particular aircraft over time in order to identify effects related to maintenance
    - For the B737-800 several winglet configurations are mixed in the data

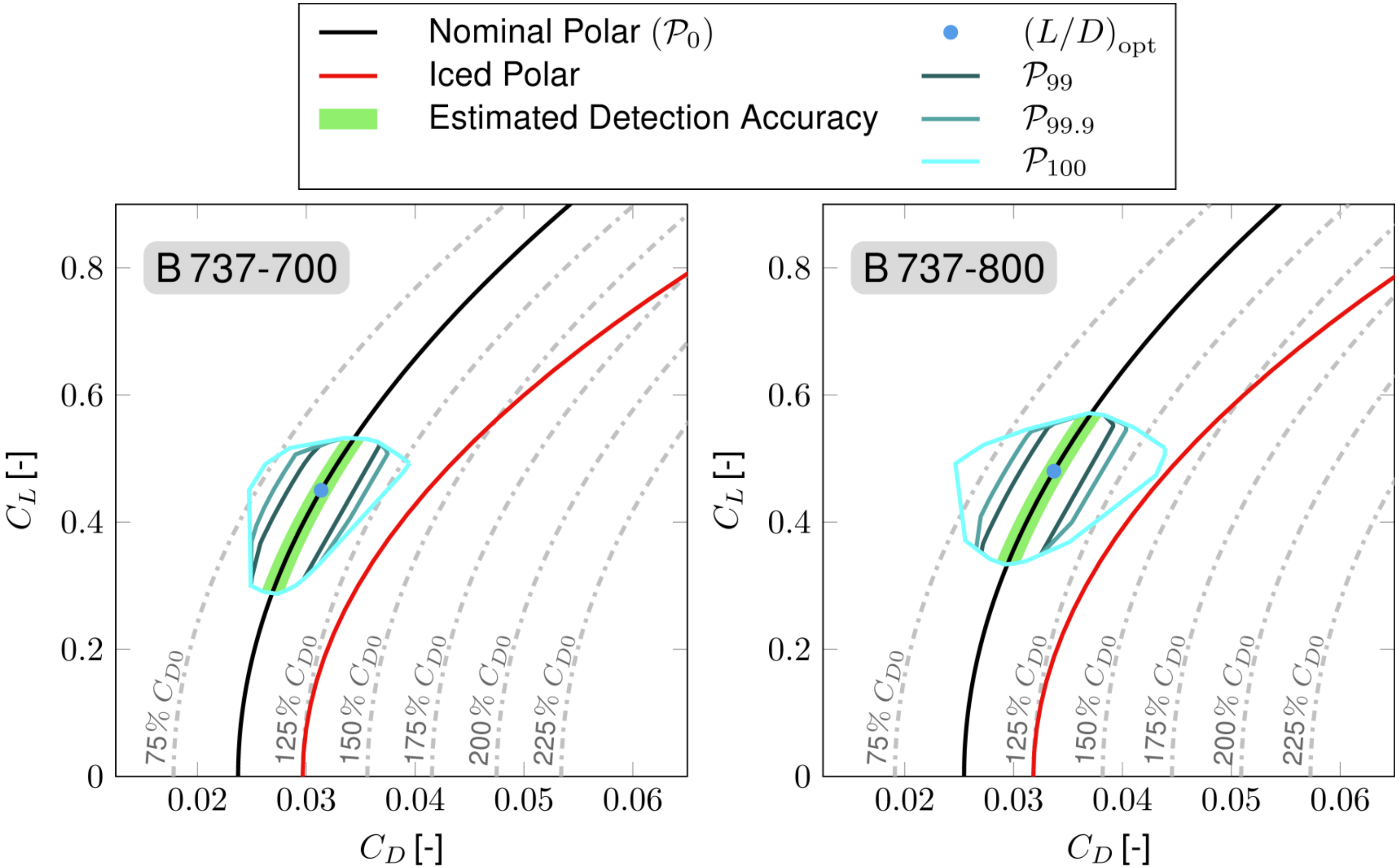


- Some of the information (e.g. engine thrust data) could be deduced from the large amount of data
  → Allowed to reduce the dispersion that was not directly linked to the ice effects or the sensor properties

Feasibility of an Ice Detection System Based on the Aircraft Performance: Data Segmentation



Feasibility of an Ice Detection System Based on the Aircraft Performance: Performance Variation



Boeing 737-700: 23,842 data sets with 202,797 flight data segments

Boeing 737-800: 51,847 data sets with 5,161,814 flight data segments

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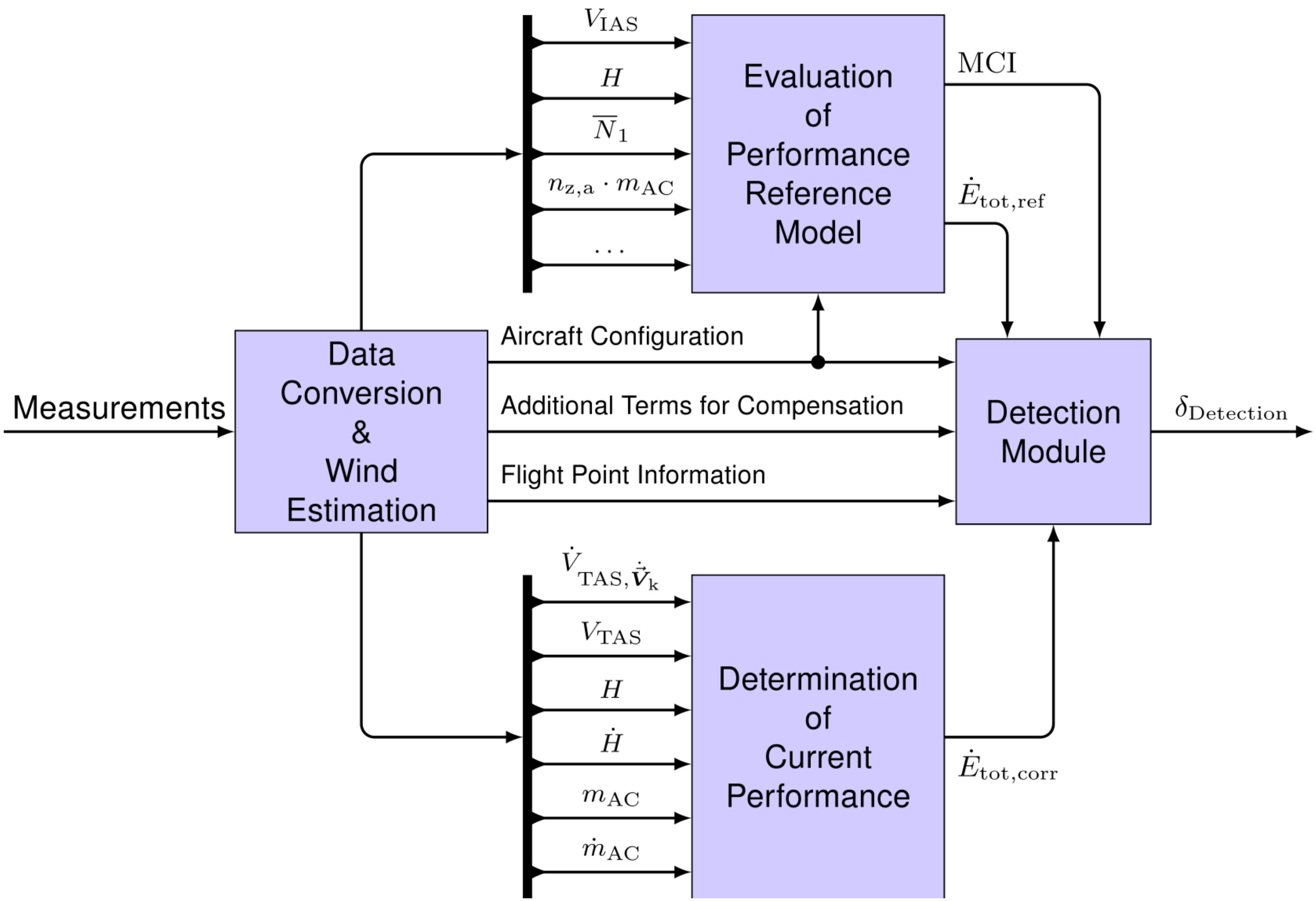
Overview of the Proposed Detection Methodology



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Overview of the Proposed Detection Methodology

- Dealing with turbulence
  → Wind estimation (Kalman filter) + low-pass filtering

- Dealing with wind change (downburst, wind shear, …)
  → Wind estimation (Kalman filter) + correction of the kinetic energy rate

$$
\begin{aligned}
\dot{E}_{\mathrm{tot,corr}} = \;& V_{\mathrm{TAS}} \cdot \dot{V}_{\mathrm{TAS},\dot{\vec{\boldsymbol{V}}}_{\mathrm{k}}} \cdot m_{\mathrm{AC}} \\
&+ \frac{1}{2} \cdot V_{\mathrm{TAS}}^2 \cdot \dot{m}_{\mathrm{AC}} \\
&+ g \cdot \dot{H} \cdot m_{\mathrm{AC}} + g \cdot H \cdot \dot{m}_{\mathrm{AC}}
\end{aligned}
$$

or equivalently

$$
\dot{E}_{\mathrm{tot,corr}} = \dot{E}_{\mathrm{tot}} - V_{\mathrm{TAS}} \cdot \dot{V}_{\mathrm{TAS},\dot{\vec{\boldsymbol{V}}}_{\mathrm{w}}} \cdot m_{\mathrm{AC}}
$$

- Dealing with sideslip even if performance models do not include sideslip effects

$$
\Delta C_{\widetilde{D}}(\beta) = \frac{\dot{E}_{\mathrm{tot,ref}} - \dot{E}_{\mathrm{tot,corr}}}{V_{\mathrm{TAS}} \cdot \overline{q} \cdot S_{\mathrm{Wing}}} - \Delta C_{D\beta,\mathrm{comp}}
$$

$$
\Delta C_{D\beta,\mathrm{comp}} = -\frac{n_{\mathrm{y}} \cdot m_{\mathrm{AC}} \cdot g \cdot \sin\beta}{\overline{q} \cdot S_{\mathrm{Wing}}}
$$

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Results

Detection of icing with no excitation (steady state flight)

- Slow accretion of ice and slow restoration of original performance

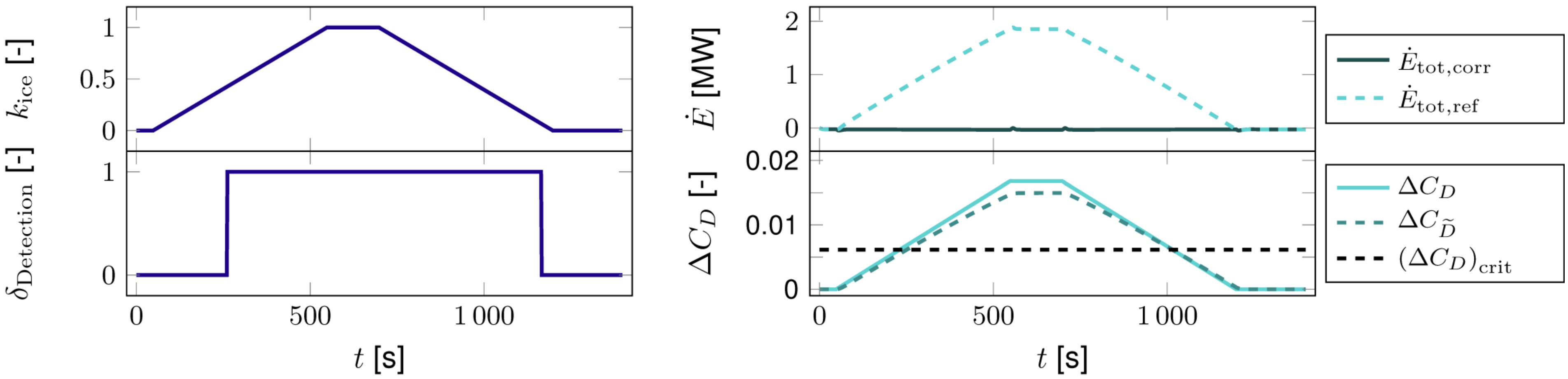
Good = detection

Check for false alarms

- In the presence of turbulence and wind shear
- During steady sideslip
- During dynamic maneuvers

Good = no false alarm (i.e. no detection)

Results – Slow Accretion of Ice and Slow Restoration of Original Performance

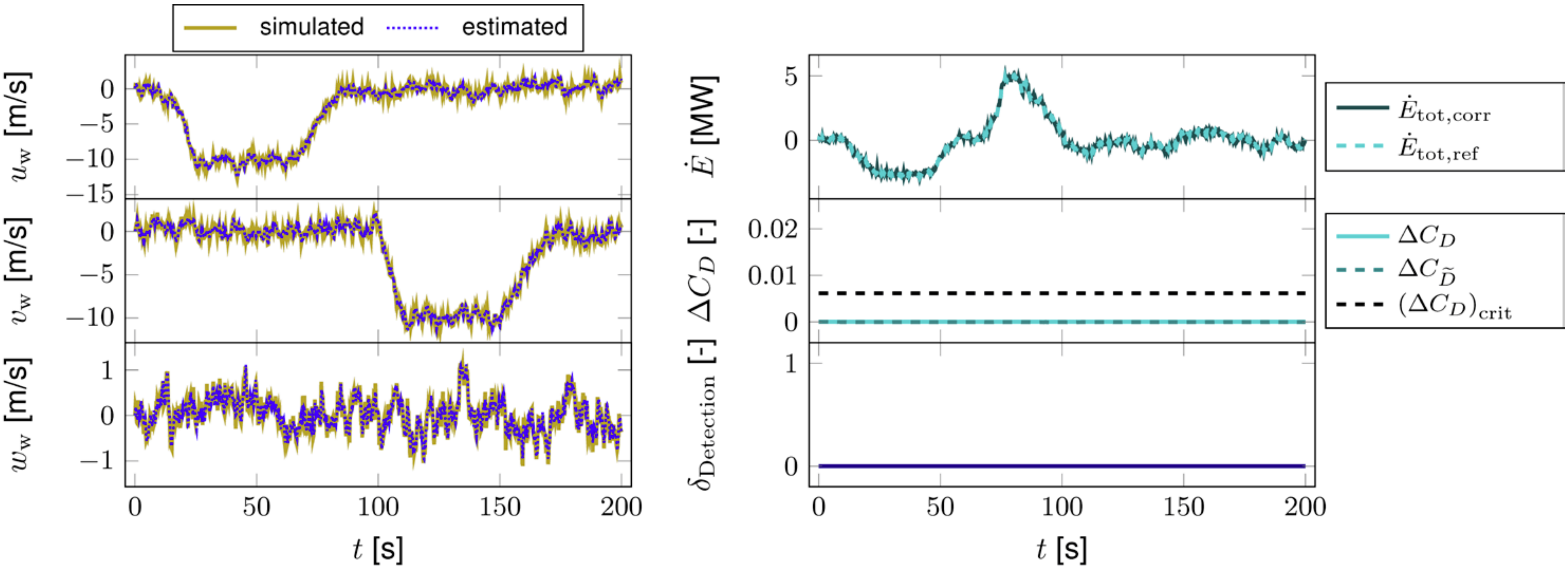


- Real power imbalance stays at zero due to the autothrust and autopilot (speed and altitude remain constant → total energy remains constant)

- But the reference model predicts a positive power imbalance

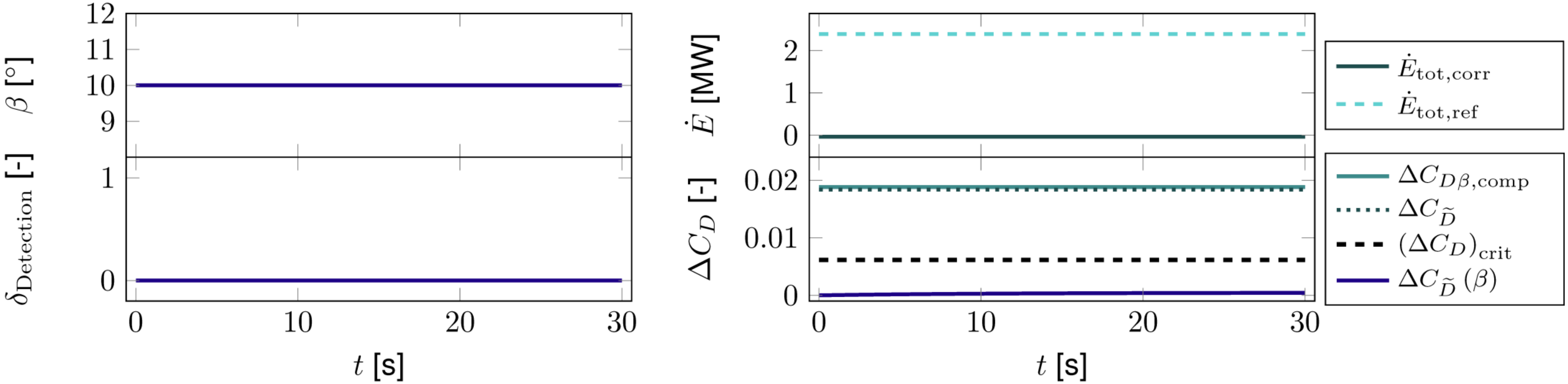
➔ Difference between both leads to trigger the detection as expected

Results – Behavior with Turbulence and Wind Shear



- The combination of turbulence and wind shear causes significant changes in energy
- The wind estimation filters the turbulence out
- The corrected power imbalance corresponds to the prediction made thanks to the performance model
  ➔ **no false detection**

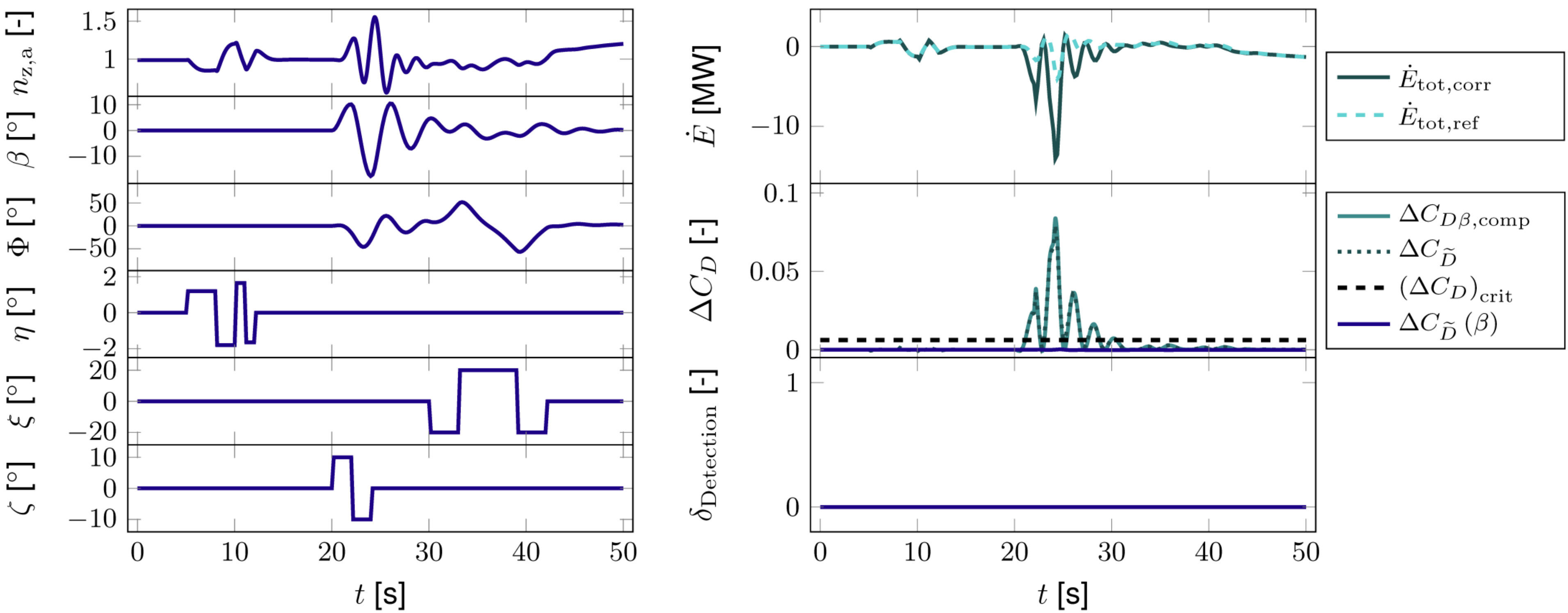
Results – Behavior During Steady Sideslip



- Constant sideslip of 10 degrees is hold (with steady heading)
- The real energy remains constant (constant speed and altitude)
- But the model (with no sideslip effect) predicts that the AC should gain energy (positive power imbalance)
  ➔ leads to an equivalent drag increase well above the detection threshold

- However, the proposed compensation term is almost equal to the computed equivalent drag increase
  ➔ **No false detection, thanks to the compensation term**

Results – Behavior During Dynamic Maneuvers



Series of maneuvers on all axes (in direct law):

- Good match in power imbalance (observed vs. model) due to pitch maneuvers
- Large deviations with sideslip
  → but here again the compensation term is precise enough
  → no false detection

Summary and Outlook

- Presented a novel ice detection methodology:
  - Based on the sensors already installed on current aircraft
  - Work during steady flight but also behaves correctly during maneuvers
  - Definition of threshold for the whole envelope made very easy through the use of a normalized "equivalent increase of the drag coefficient"
- Fine tuning of threshold values for specific requirements still to be done (trade-off between detection sensitivity and probability of false alarms)
- Sensitivity to measurement uncertainties is currently being performed and will be published soon (probably at AIAA Aviation 2017)
- Current work on the associated HMI and cockpit procedures
- Hybridization with other ice detection systems?
  (to enable better trade-offs between reliability and sensitivity)
- <u>Patent pending on the method and the system</u>
- <u>Maturation ideally in cooperation with aircraft manufacturers and operators</u>

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